

# FLIGHT PERFORMANCE EVALUATION OF THREE GPS RECEIVERS FOR SOUNDING ROCKET TRACKING

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## BIOGRAPHY

Mr. Bull is an Electrical Engineer in the Guidance, Navigation and Control (GN&C) Center of NASA's Goddard Space Flight Center. Mr. Bull's primary responsibilities are in development of GPS systems for sub-orbital payloads on balloons, sounding rockets and remote sensing aircraft platforms. He received a BS degree in Aerospace and Ocean Engineering from Virginia Polytechnic Institute and State University in 1980. He joined NASA in 1990 as a Systems Engineer for the TOPEX Radar Altimeter.

Mr. Diehl is a Telemetry/Instrumentation Engineer in the Electrical Engineering Group under the NASA Sounding Rocket Operations Contract (NSROC). He is employed by Northrup Grumman IT at NASA's Wallops Flight Facility (WFF). Mr. Diehl's primary responsibilities are in Telemetry and GPS systems for use on sounding rocket payloads. He received a B.S. degree from Southwest Missouri State University in 1980. Since 1980, he has been working at WFF providing Telemetry Systems and support for numerous sounding rocket missions at various launch sites around the world. Since 1998, he has been involved with integrating various GPS receivers into sounding rocket platforms and post-mission analysis of GPS flight data.

Mr. Montenbruck is head of the GPS Technology and Navigation Group at DLR's German Space Operations Center (GSOC). He received his Ph.D. from Munich's University of Technology in 1991. Since 1987 he's been working at DLR/GSOC as a flight dynamics engineer,

where he specialized in satellite orbit determination. His current field of work comprises the development of on-board navigation systems and spaceborne GPS applications. He's written various text books on computational astronomy and satellite orbits.

Mr. Markgraf is a GPS development engineer at DLR/GSOC. He has prepared and conducted various sounding rocket flight experiments at Esrange, Kiruna, Sweden and is in charge of the mission preparation and operations for the IRTD-2 GPS experiment.

## ABSTRACT

In preparation for the European Space Agency Maxus-4 mission, a sounding rocket test flight was carried out at Esrange, near Kiruna, Sweden on February 19, 2001 to validate existing ground facilities and range safety installations. Due to the absence of a dedicated scientific payload, the flight offered the opportunity to test multiple GPS receivers and assess their performance for the tracking of sounding rockets.

The receivers included an Ashtech G12 HDMA receiver, a BAE (Canadian Marconi) Allstar receiver and a Mitel Orion receiver. All of them provide C/A code tracking on the L1 frequency to determine the user position and make use of Doppler measurements to derive the instantaneous velocity. Among the receivers, the G12 has been optimized for use under highly dynamic conditions and

has earlier been flown successfully on NASA sounding rockets [1]. The Allstar is representative of common single frequency receivers for terrestrial applications and received no particular modification, except for the disabling of the common altitude and velocity constraints that would otherwise inhibit its use for space application. The Orion receiver, finally, employs the same Mitel chipset as the Allstar, but has received various firmware modifications by DLR to safeguard it against signal losses and improve its tracking performance.

While the two NASA receivers were driven by a common wrap-around antenna, the DLR experiment made use of a switchable antenna system comprising a helical antenna in the tip of the rocket and two blade antennas attached to the body of the vehicle.

During the boost a peak acceleration of roughly 17g's was achieved which resulted in a velocity of about 1100 m/s at the end of the burn. At apogee, the rocket reached an altitude of over 80 km. A detailed analysis of the attained flight data is given together with a evaluation of different receiver designs and antenna concepts.

## 1 INTRODUCTION

The Maxus 4 Test project, a joint venture between the Swedish Space Corporation (SSC) and DLR, Germany, was undertaken for personnel training and equipment verification at Esrange. Three GPS experiments flew on an Improved Orion sounding rocket: a modified Mitel Orion receiver (the similarity to the rocket's name is coincidental) built by DLR, and two receivers supplied by NASA; an Ashtech G12 based NASA/GSFC/WFF sounding rocket receiver and a BAE (Canadian Marconi) Allstar.

The launch was a practice flight for the larger Maxus-4 rocket to be used by ESA for microgravity experiments. At 81 km, the maximum altitude was lower than many sounding rockets, but the dynamics were typical of other missions. Maximum acceleration was 17 g's and the total velocity peaked in excess of 1100 m/s. The payload spun at about 4 rps until it was despun after separation from the booster.

The NASA payload section consisted of two GPS receivers and the Flight Modem being developed under the Advanced Range Technology Initiative (ARTI).

The WFF Ashtech receiver was used as a data source for a NASA Flight Modem demonstration and by the range to provide real-time predictions of the missile impact point. A real time differential solution was performed on the downlinked data.

The BAE Allstar receiver was included because it is much less expensive than the G12 unit and is readily available with waivers to COCOM limits. WFF is using the receiver for balloon applications and a test was desired to evaluate it for use on sounding rockets.

Available experience with commercial-off-the-shelf (COTS) GPS receivers shows that various models can provide continuous tracking of sounding rockets under favorable conditions. On the other hand, large tracking gaps have been observed, which indicates that temporary signal losses cannot be handled properly and that a reacquisition under highly dynamical motion is hard to achieve. To enhance the tracking robustness and reliability, adaptations of the standard receiver software need to be performed, which prohibits the use of most COTS receivers. The Mitel Orion receiver has therefore been selected for the implementation of a GPS based tracking system for sounding rockets, since it supports software modifications through the Mitel Architect development system [2].

### 1.1 Receivers

#### 1.1.1 NASA Payload Receivers

The Ashtech G12 HDMA, a small, light receiver with 12 parallel channels supports a number of data output formats allowing flexibility in development. Most importantly, it has proven adept at tracking during the high accelerations and velocities of boosters and quick reacquisition when it loses lock. It is integrated into a 3" x 5" x 1" aluminum box with a support board designed and fabricated at Wallops to perform three functions; power conditioning, communications format conversion, and battery backup to programming. NASA has used this receiver successfully since 1997 to track a variety of sounding rockets at ranges throughout the world.

The G12 receiver has two output ports. Binary data containing position, velocity, time, and housekeeping data as well as pseudorange data necessary to compute a differential solution was sent to both ports at a 2 Hz rate. One port was routed to the Flight Modem computer and stored in on board memory. The second went to a conventional telemetry system and was downlinked to the tracking station. This port also contained the ASCII NMEA "POS" message at a 10 Hz update rate and was used by the range tracking system.

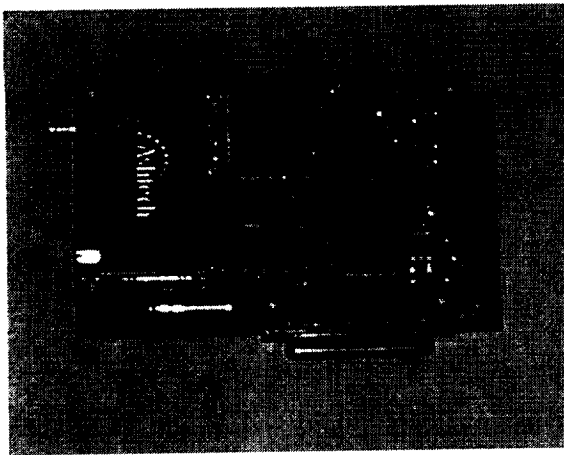


Fig 1. Ashtech G12 HDMA Receiver

The BAE Allstar is a 12 Channel OEM receiver based on the Mitel chip set. It supports a variety of data formats including carrier phase at several selectable rates. It was flown in the Starbox packaging for ease of integration.

### 1.1.2 DLR Receiver

The GPS receiver has been built up at DLR/GSOC based on the ORION receiver design of Mitel Semiconductor. It employs the GP2015/2020 front-end and 12 channel correlator chipset as well as an ARM60B 32-bit microprocessor. The original firmware has been enhanced to cope with the highly dynamical environment of ballistic trajectories and the TM/TC interface has been adapted for space applications [3]. The Orion receiver unit flown as part of the Test Maxus-4 mission is shown in Fig. 2

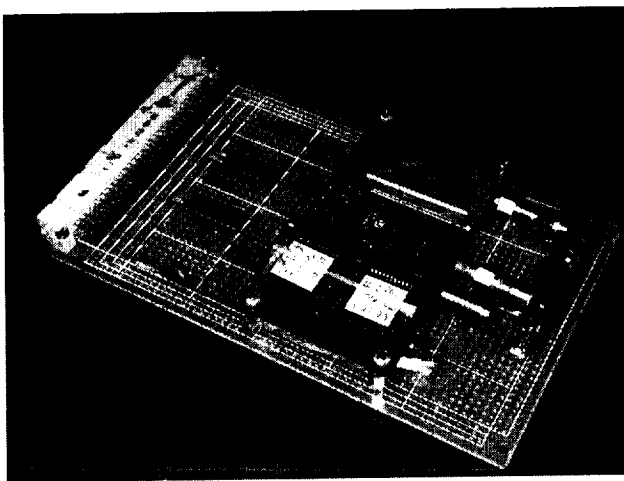


Fig 2. Orion Receiver

## 1.2 Antennas

### 1.2.1 NASA Antenna and Preamplifier

Both NASA GPS receivers shared a common airborne antenna and an external low noise amplifier (LNA) or pre-amp.

The antenna was designed by New Mexico State University Physical Science Laboratory (NMSU/PSL). It consists of eight radiating elements fabricated on two 1/8" thick by 5.5" width half rings which are joined together and flush mounted in a groove milled into the skin of the rocket's payload section. The two subarrays are fed in-phase with a coaxial power divider harness. A radome is incorporated into each subarray to protect against heat.

The pattern is fairly circular with -8dBic at 90% full coverage. Due to the elements being fed in-phase, a null of 3 to 5 dB at the 3dB down level exists along the axis of the rocket. The VSWR is approximately 2 with a bandwidth of about 10 MHz.

### Preamplifier

The combined signal is routed to a Trimble preamplifier that provides 42dB of gain. Power is provided via the coaxial cable. The frequency range is 1565 to 1585 MHz with excellent rejection of out of band signals.

### 1.2.2 DLR Antenna System

To support the different mission phases and to assess the suitability of different antenna concepts, the rocket was equipped with a newly designed multi-antenna system [4]. A helical antenna mounted in the tip of the rocket cone provided near hemispherical coverage during the ascent trajectory. After separation of the cone, an R/F switch connected the GPS receiver to a pair of blade antennas mounted opposite to each other on the walls of the recovery module and combined via a power divider. This provided a near omni-directional coverage and allowed tracking of a sufficient number of satellites even for the tumbling motion of the payload module during the re-entry into the dense part of atmosphere.

A detailed view of the utilized antenna system is provided in Fig. 3. Depending on the mission phase, one out of three antenna systems (ground, tip, can) was connected to the RF input of the GPS receivers via a set of R/F switches. The switching between the different antennas was controlled via telecommand and a break wire. Each antenna carries its own pre-amplifier, powered by a dedicated current limited supply. To avoid interference with a Globalstar flight modem flown on the adjacent payload segment, a narrow bandpass filter was inserted into the R/F signal branch of the blade antenna system.

Furthermore, a notch filter was inserted in the tip antenna branch to reject radiation from the S-band transmitters.

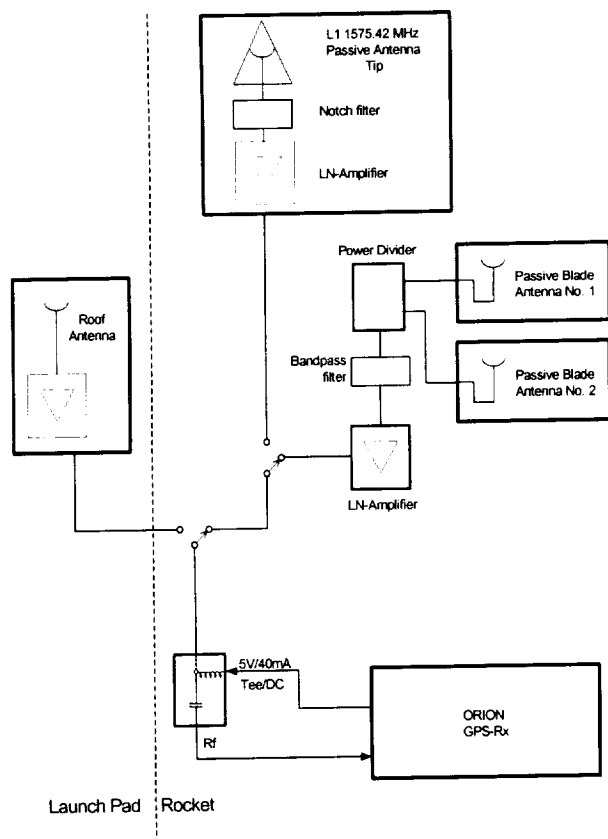


Fig. 3 DLR Antenna System

### 1.3 Flight Configuration

The payload, as illustrated in Fig. 4, was comprised of a DLR recoverable nosecone, a NASA GPS/Flight modem section, a Swedish Space Corporation (SSC) service module, a DLR payload section, and a DLR recovery/ignition module. The SSC service module provided +28V power & switching for the GPS receivers, PCM encoder, & flight modem. The SSC service module also provided the S-Band telemetry transmitter and antenna.

The Orion receiver was placed inside the DLR service module, which housed a data handling unit and telemetry system. In addition, the two blade antennas were attached to the walls of the service module.

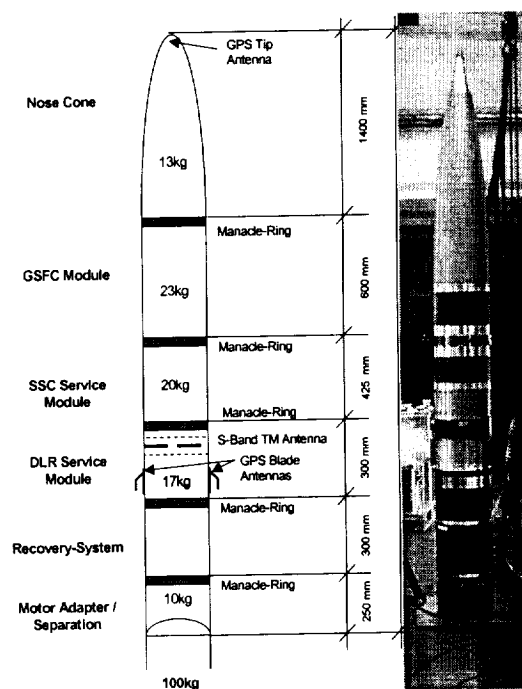


Fig. 4 Mission Configuration

### 1.4 Mission Profile

During the 24 sec boost phase, the rocket built up a spin rate of 3.8 Hz about the longitudinal axis. Accordingly, the rocket maintained a constant and stable attitude with a near zenith-facing tip. In the first 6 sec boost phase, a maximum acceleration of 17g's was reached. After burnout a maximum rate of climb of 1100 m/s and a speed over ground of 280 m/s were measured. The rocket reached the apogee 2 minutes and 17 seconds after lift-off at an altitude of 81 km. Briefly, thereafter, the spin was removed by a yo-yo system and the top cone as well as the motor were separated (Fig. 5). The service and recovery module started a tumbling motion from about 40 km altitude downwards. Between 25 and 15 km altitude the module decelerated to sub-sonic speed before parachute deployment at an altitude of 5 km. The payload and nose cone landed at a distance of 60 km from the range and were recovered by helicopter.

The velocity and altitude profile are illustrated in Fig. 6. The ground track is in Fig 7.

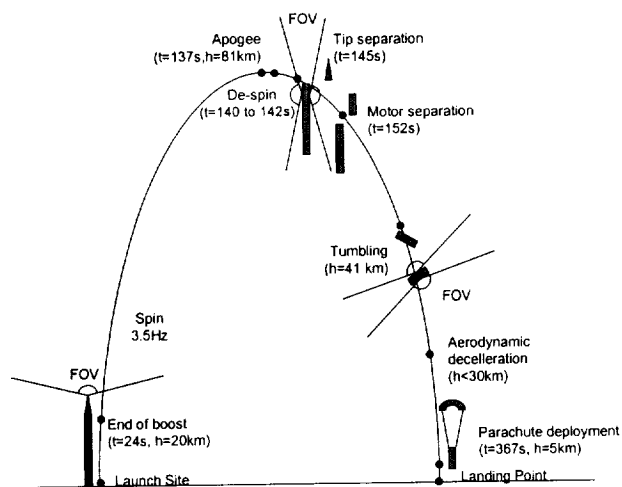


Fig. 5 Mission Profile

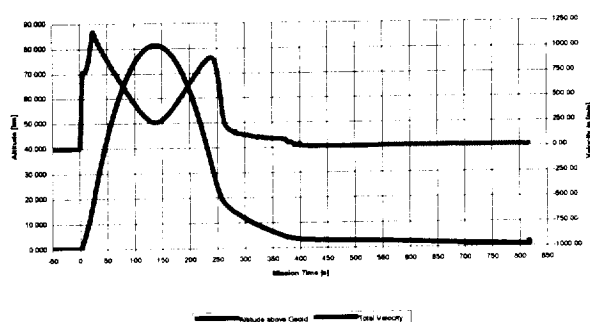


Fig. 6 Altitude and Velocity

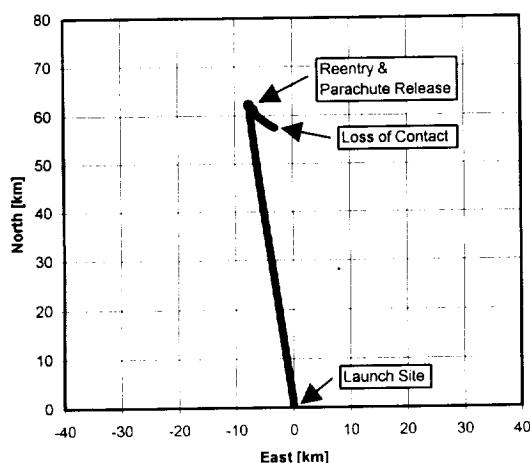


Fig. 7 Ground Track

## 2 RESULTS AND ANALYSIS

### 2.1 Tracking

Fig. 8 shows the number of satellites being tracked by each of the receivers throughout the flight. Please note that due to limitations of the plotting program, the scale of the left side Y-axis runs from 0 to 50 and cannot be made to repeat for each receiver. Offsets are therefore applied to the data from the Orion and Allstar receivers' data as noted on the plot. Fig. 8 also shows the acceleration of the payload as derived from the velocity reports of the G12 receiver.

Given the impact of acceleration and jerk on the tracking capabilities of GPS receivers, it is useful to consider the flight as consisting of five phases; prelaunch, boost, free flight, reentry and final descent.

All receivers were turned on and had acquired data prior to launch (Mission Time = 0). At this time, both the Allstar and the Orion were tracking 9 SVs each and the G12 had 8.

At liftoff, all receivers responded with loss of some SVs. The Improved Orion rocket is a single stage vehicle, but has two separate boost periods. These are seen as two separate peaks in acceleration in the first 25 seconds of flight. During this period the payload is subjected to the maximum acceleration and jerk. The G12 and Orion dropped to as low as 6 SVs in the case of the G12 and 5 for the Orion, but retained lock and within 8 to 9 seconds regained the full complement of SVs that existed at launch. The loss and reacquisition of SVs that existed at launch is not uncommon, nor totally unexpected, since the payload is leaving the presence of a high RF multi-path environment (launch rail) and subjected to large jerk and acceleration. From this point until apogee, both receivers acquired more low elevation satellites as altitude increased. Within 18 seconds, the G12 was tracking 11 SVs. The Allstar lost lock completely at lift off and did not reacquire the requisite 4 SVs until 7 seconds into the flight. Even then, it consistently tracked fewer SVs than the other receivers.

All receivers performed well after rocket motor burnout during the unpowered, free flight until re-entry. This phase included apogee, despin of the payload and separation of the top cone which switched the DLR Orion receiver to the stub antenna system.

During reentry of the payload into the atmosphere, accelerations occur from 245 sec to 290 sec. Some decrease in the number of SVs tracked occurred for each receiver. While the Orion saw only a temporary drop of 4 SVs, both the NASA supplied G12 and Allstar receivers were much more seriously affected and actually lost lock on sufficient satellites necessary to compute solutions.

Close examination shows that while the losses by the Orion and a loss by the G12 of two SVs (one of which recovered) occurred at the time of the highest accelerations associated with the reentry, there is a lag of some seconds before the loss of lock by the two NASA receivers. The G12 began to lose SVs at about T+277 sec, reached a low of 2 at T+292 sec and had reacquired 8 SVs by about T+325 sec. The Allstar exhibited similar behavior to a much worse degree from T+271 sec to T+328 sec.

The lag of time before the large losses and the relatively benign acceleration compared to the launch stresses indicates that interference with the tracking is caused by some other affect. Two likely candidates have been suggested: interference with the antenna coverage due to pitch/yaw motion and heating of the antenna. Both theories are based on the fact that the two receivers share a common antenna.

Accelerometer data (Fig. 9) shows a strong oscillation in the pitch and yaw axes of the payload. While the wrap around antenna has excellent coverage in the roll plane, such antennas have on axis nulls. The null is expected to be 6-7 degrees wide at -10dB level. Since actual patterns on this payload are not available, the width of the null could be somewhat larger and it is conceivable that the nulls were aligned with some of the SVs at various times, interfering with tracking.

A more likely explanation is a rise in the noise floor caused by antenna heating by friction with the atmosphere. Fig 10 shows that a slight lowering of the C/No occurs at the time SVs are lost. No temperature data exists for the flight, but it is known that reentry can raise the temperature of a payload skin by well over 100 deg F, in turn raising the noise floor of the signal. During situations in which the signal strength is marginal, this could cause loss of reception on SVs of lower signal level.

Final ascent tracking was optimal except for a short loss of SVs by the NASA receivers when the parachute was deployed. Again, the Allstar was more seriously affected.

## 2.2 Accuracy

Due to the absence of a reference trajectory or a tracking system that can be expected to perform better than GPS, the accuracy of the three GPS receivers during the Test Maxus-4 flight can only be assessed in a relative way. Given the fact that the Astech G12 HDMA receiver has the best flight history, provides smooth and self-consistent position and velocity measurements at a high output rate and is specifically designed to handle high dynamics (tracking loops, oscillator, etc.), it was decided to

compare the navigation solution of the Orion and Allstar receivers against the G12 reference.

In case of the Orion receiver, post-processed single-point solutions based on raw pseudorange and Doppler measurements at a 2 sec update rate were used in this comparison, while the Allstar navigation solution could be employed directly. This is due to the fact that, a simple box-car filter of the standard Orion GPS firmware was unintentionally activated during the flight and degraded the onboard position velocity solution under the high dynamics. The post-processed solutions match the receiver internal solution prior to the filtering and thus provide an unbiased picture of the actual tracking performance. Furthermore, it is noted that an interpolation of the G12 navigation solution to the time of the Orion measurements was required, since the early release of the Orion flight software did not yet provide for an alignment to integer UTC or GPS seconds.

Table 1 GPS Orion tracking accuracy compared to G12

| Flight Phase | Mean [m] |     |      | RMS [m] |      |       | Max [m] |
|--------------|----------|-----|------|---------|------|-------|---------|
|              | X        | Y   | Z    | X       | Y    | Z     |         |
| Launch site  | 0.9      | 2.2 | 4.9  | 3.6     | 2.2  | 14.7  | 39.7    |
| Boost phase  | 8.8      | 3.9 | -0.2 | 26.6    | 29.6 | 114.5 | 341.1   |
| Free flight  | -1.2     | 1.2 | -0.3 | 1.0     | 0.8  | 3.1   | 12.8    |
| Reentry      | -6.2     | 8.3 | 0.7  | 20.4    | 25.8 | 19.9  | 120.1   |
| Descent      | 0.6      | 1.9 | 0.7  | 1.3     | 1.3  | 2.4   | 6.9     |

Table 2 BAE Allstar tracking accuracy compared to G12

| Flight Phase | Mean [m] |      |       | RMS [m] |     |      | Max [m] |
|--------------|----------|------|-------|---------|-----|------|---------|
|              | X        | Y    | Z     | X       | Y   | Z    |         |
| Launch site  | -1.9     | 4.7  | -19.4 | 2.7     | 1.9 | 5.4  | 28.9    |
| Boost phase  | 0.2      | 1.9  | -14.6 | 5.3     | 4.4 | 12.3 | 43.8    |
| Free flight  | 1.0      | 0.3  | -1.5  | 1.1     | 0.3 | 4.0  | 18.1    |
| Reentry      | -0.7     | -0.0 | -3.9  | 0.9     | 0.3 | 1.3  | 8.1     |
| Descent      | -2.5     | 0.0  | -5.5  | 0.7     | 0.7 | 2.3  | 13.7    |

Statistics of the Orion and Allstar position errors with respect to the G12 reference are summarized in Tables 1 and 2, respectively, for the various flight phases. Two major aspects may readily be identified, in which the performance of the Allstar and Orion receiver differ from each other, namely tracking performance under high dynamics and data noise.

Despite the fact that the Orion receiver maintained lock during the high dynamics boost and reentry phase, it shows notably larger position errors than the Allstar receiver over the selected time intervals. This is likewise true for the velocity solution that is highly degraded during the first boost phase. On the other hand, signal simulator tests carried out independently with the Orion

receiver show that the applied code DLL and carrier FLL have no difficulties following the encountered signal dynamics during the Test Maxus-4 flight. In addition, the Orion receiver was later observed to properly track the boost phase of the main Maxus-4 mission with a smooth increase of the acceleration of to a peak value of about 11g, but to encounter problems again near the end of boost. Therefore, it is concluded that the bad tracking performance is actually due to mechanical stress of the employed 10 MHz crystal oscillator during phases of high jerk (i.e. acceleration changes). Further flight tests will be required to trace down this source of errors and identify more suitable oscillator types.

During the stationary pre-launch phase and the parabolic free-flight phase, the tracking accuracy of the Orion and Allstar receivers is generally comparable. In both cases the results are consistent with the G12 solution to the order 10m, which is all that can be expected for the Standard Positioning Service available to a common C/A code receiver in the absence of Selective Availability. In view of remaining broadcast ephemeris errors and deficiencies of the ionospheric correction model, individual pseudoranges cannot be modeled consistently making the solution dependent on the actual set of satellites tracked.

In the case of the Orion receiver the free flight position solutions exhibit a short term noise of one to three meters in each axis, which is consistent with the respective PDOP values and a raw pseudorange noise of about 0.5-1.5m determined independently from post-processed single point solutions. The Allstar receiver, in contrast, applies carrier phase smoothing (as does the G12), which effectively removes the short term noise. Minor steps in the Allstar-G12 position offset may, however, be observed, that are probably caused by resets of the filter employed within the smoothing process. The carrier phase smoothing may also be responsible for the low noise but high bias between the G12 and Allstar solutions observed in the high multipath environment of the launch pad. The Orion receiver in contrast performs no smoothing and reacts more rapidly on changing multipath effects. Thus, its position solutions match the G12 values on average but exhibit more pronounced fluctuations over time scales of several minutes.

## SUMMARY

The ability of GPS receivers to track a high dynamics sounding rocket is well established although some maneuvers such as occurred during re-entry can lead to temporary loss of lock. The Ashtech G12 HDMA, through frequent usage has served as a standard for performance. It is shown here that other, less expensive receivers may also be capable of good performance. However, as illustrated by the superiority of the Orion

over the Marconi Allstar, both based on the same chipset, careful attention must be paid to the design of the tracking and filtering firmware. The importance of high quality reference oscillators is also indicated.

On vehicles which either do not spin, or on which a forward pointing antenna may be accommodated, money and weight may be saved by omission of a wraparound antenna.

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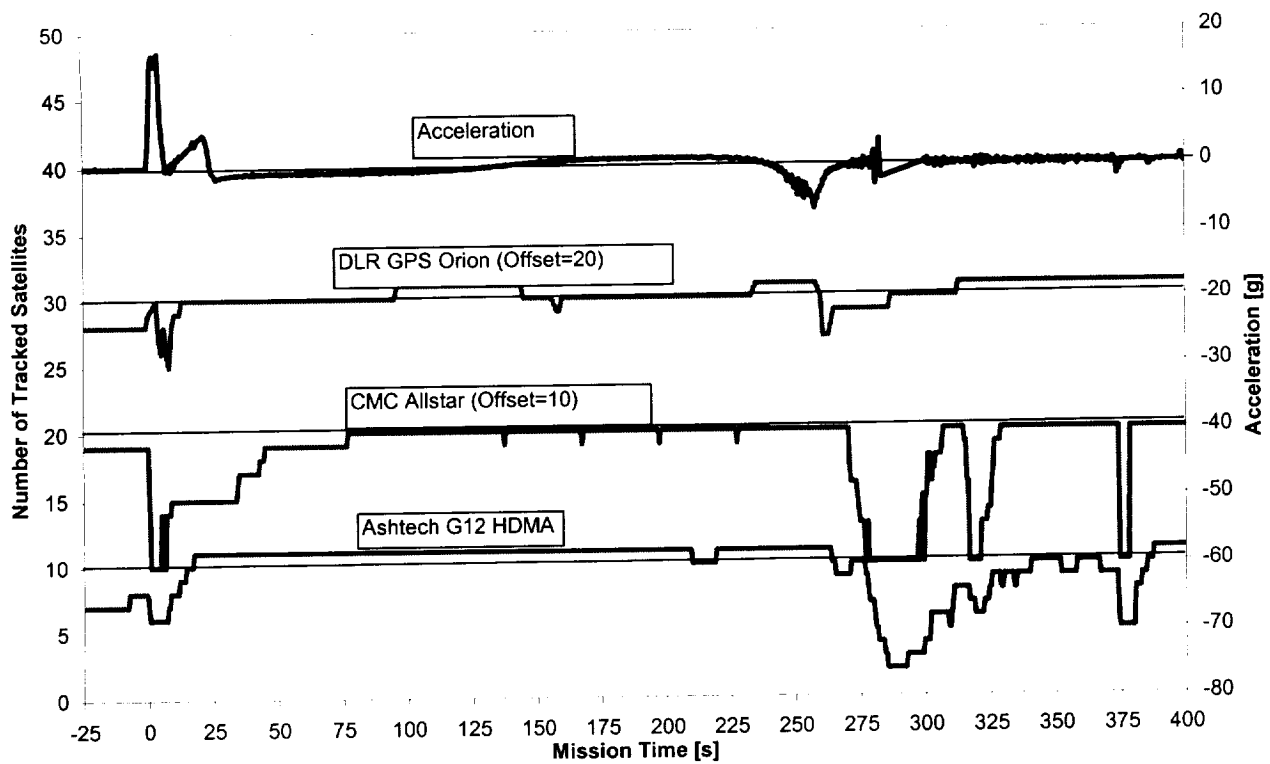


Fig 8 Satellites Tracked

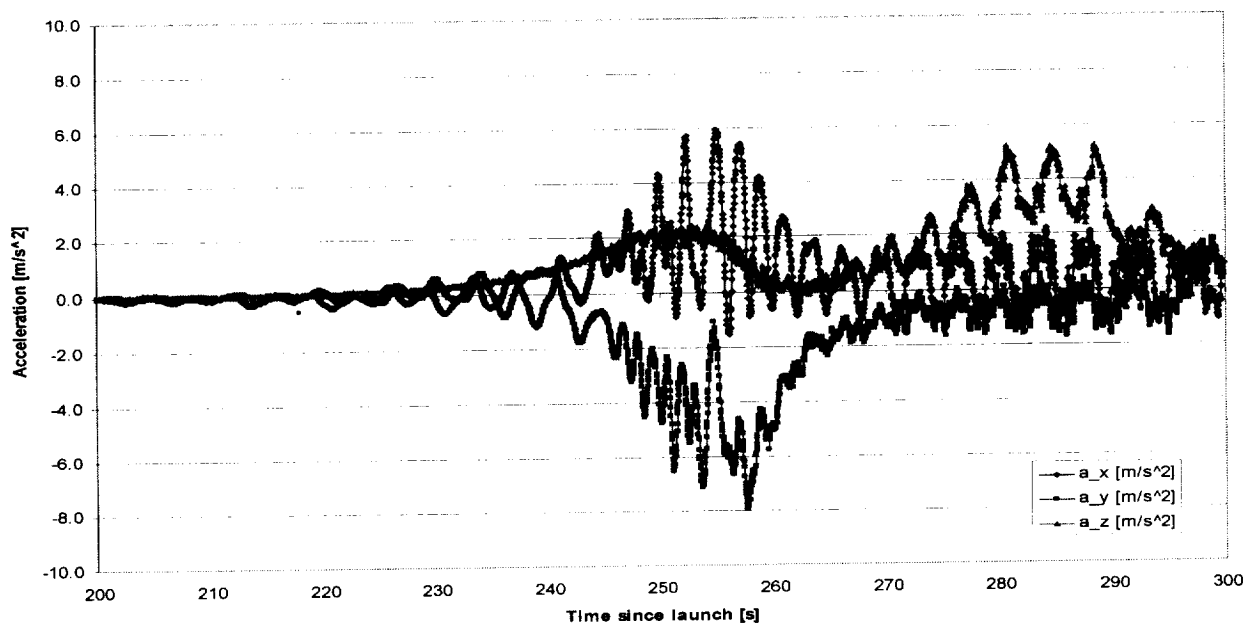


Fig. 9 Accelerometer Data Re-entry Phase



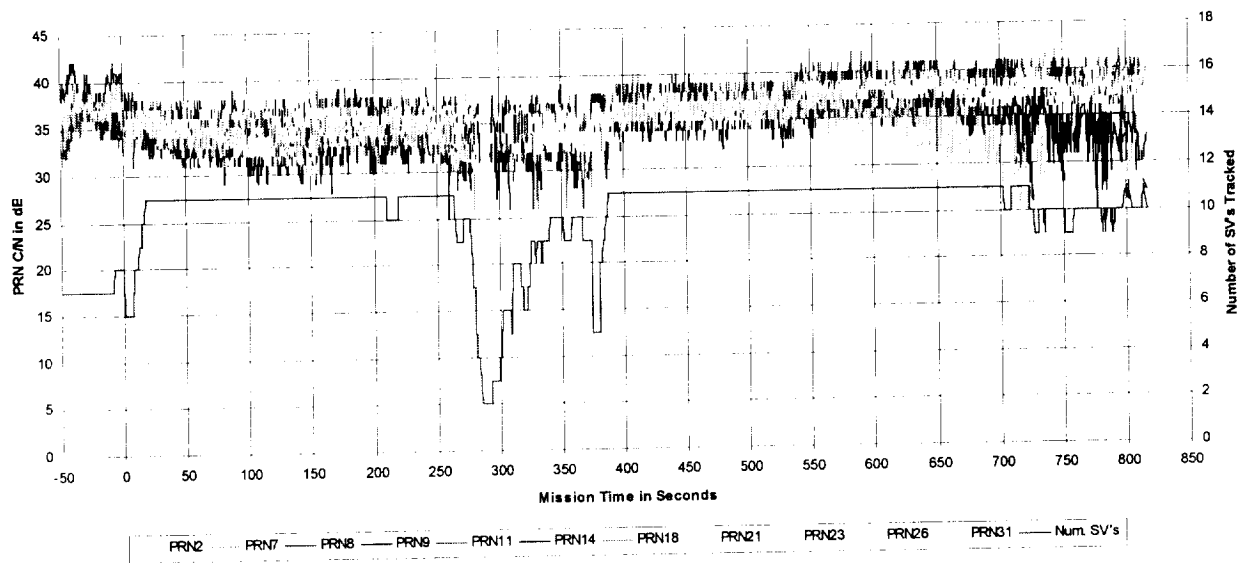


Fig. 10 Signal Strength and Number of SVs